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Chemical and mechanical instability in hot isospin-asymmetric nuclear matter

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Using phenomenological equations of state, we study the chemical and mechanical instabilities in hot isospin-asymmetric nuclear matter. Both instabilities are found to depend strongly on the isospin asymmetry of the nuclear matter. For a chemically and mechanically stable asymmetric nuclear matter, a lower neutron excess is found in the liquid phase than in the gas phase. Furthermore, the neutron excess in the mixed phase at densities between that of the liquid and the gas phases is limited by certain maximum value. Also, for the nuclear equations of state considered here the boundary of chemical instability in the pressure-density plane is found to be more extended than that of mechanical instability. However, locations of these boundaries depend sensitively on both the bulk compressibility of nuclear matter and the density dependence of the symmetry energy.

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I. INTRODUCTION

During the last decade, there have been extensive studies on multifragmentation in nuclear reactions, which is characterized by the emission of several intermediate mass fragments with a power law distribution. It has been suggested that this phenomenon is due to various mechanical instabilities of the nuclear matter, such as the volume instability, the surface instability of the Rayleigh kind, and the Coulomb instability. A recent review on nuclear multifragmentation can be found in ref. [1]. With radioactive ion beams, which have been successfully developed recently, nuclear matter with a high isospin asymmetry can be created transiently during reactions induced by neutron-rich nuclei (e.g., [2,3]). This thus offers the possibility to study also the chemical instability associated with the isospin asymmetry of the nuclear matter. Indeed, recent experiments on nuclear reactions involving different ratios of the neutron to proton numbers have shown that products from nuclear multifragmentation depends strongly on the isospin asymmetry of the colliding nuclei [4–6].

It is well-known that nuclear matter is not thermodynamically stable at all densities ρ, temperatures T, and neutron excess $\delta \equiv (\rho_n - \rho_p)/\rho$. The necessary and sufficient conditions for the existence of a stable isospin-asymmetric nuclear matter can be expressed by the following inequalities (e.g., [7–9]):

$$\left(\frac{\partial E}{\partial T}\right)_{\rho,\delta} > 0, \tag{1}$$

$$\left(\frac{\partial P}{\partial \rho}\right)_{T,\delta} \geq 0, \tag{2}$$

$$\left(\frac{\partial \mu_n}{\partial \delta}\right)_{P,T} \geq 0, \tag{3}$$

where E, P, and μ_n are the energy per nucleon, pressure and neutron chemical potential, respectively. The first condition is required by the thermodynamic stability and is always satisfied by any reasonable nuclear equation of state; the second condition ensures the mechanical stability against the growth of density fluctuations; and the last one protects the chemical or diffusive stability (DS) against the development of neutronization. The last two

conditions can be violated in some regions of the (ρ, T, δ) configuration space, leading to mechanical and/or chemical instabilities.

The boundaries of mechanical and chemical instabilities in the (ρ, T, δ) space depend on the equation of state (EOS) of asymmetric matter. In the Relativistic Mean-Field (RMF) theory, which has a linear density dependence in the symmetry energy, recent studies indicate that the diffusive spinodal associated with the chemical instability of asymmetric nuclear matter encloses more of the configuration space than the isothermal spinodal associated with the mechanical instability [9]. For values of isospin asymmetry, $\delta \leq 0.4$, which are reachable in reactions induced by neutron-rich nuclei, the separation between the isothermal and diffusive spinodals in $P - \rho$ plane is significant, and the diffusive instability becomes a more relevant spinodal in discussing the properties of asymmetric nuclear matter.

However, the density dependence of nuclear symmetry energy is poorly known, and theoretical predictions vary widely [10–16]. Although it is linear in density in the RMF theory, a $\rho^{1/3}$ dependence was obtained by Siemens using the Bethe-Goldstone theory for asymmetric nuclear matter [10]. More sophisticated calculations by Wiringa *et al.* using the variational many-body theory [13] give different density dependence depending on the nuclear forces used in the calculations. It is thus both interesting and necessary to examine how the structure of mechanical and chemical instabilities in asymmetry nuclear matter might change when other nuclear equations of state are used.

The nuclear symmetry energy at densities other than the normal nuclear matter density is of interest in both astrophysics and nuclear physics. For example, the cooling rate, chemical composition and magnetic moment of a neutron star depend critically on this [15,17,18]. For nuclear reactions induced by neutron-rich nuclei, it was recently found that the nuclear symmetry energy affects significantly the reaction dynamics, especially the ratio of preequilibrium neutrons to protons emitted in the early stage of heavy-ion collisions at intermediate energies [19].

In the present paper, we study the chemical and mechanical instabilities of asymmetric nuclear matter using various phenomenological equations of state. These EOS's have been

used previously by us in studying the ratio of preequilibrium neutrons to protons in nuclear reactions induced by neutron-rich nuclei. In particular, we examine the dependence of the boundaries of these instabilities on both the compressibility and the density dependence of the symmetry energy. We find that for all equations of state considered here a similar conclusion as that based on the RMF is obtained, i.e., the isothermal spinodal is enclosed within the diffusive spinodal, and the location of these two spinodals depends sensitively on both the bulk compressibility of nuclear matter and the density dependence of the symmetry energy.

II. THERMODYNAMICAL ANALYSIS OF CHEMICAL AND MECHANICAL INSTABILITIES

For asymmetric nuclear matter in thermal equilibrium, the density ρ_q of neutrons ($q = n$) or protons ($q = p$) is

$$\rho_q = \frac{1}{\pi^2}\int_0^\infty k^2 f_q(k) dk, \tag{4}$$

where

$$f_q(k) = [\exp(e_q - \mu_q)/T + 1]^{-1} \tag{5}$$

is the Fermi distribution function, and e_q is the single particle kinetic energy. For modestly high temperatures ($T \geq 4$MeV), this equation can be inverted analytically to obtain the chemical potential [20–22]

$$\mu_q = V_q + T\left[\ln(\frac{\lambda_T^3\rho_q}{2}) + \sum_{n=1}^{\infty}\frac{n+1}{n}b_n(\frac{\lambda_T^3\rho_q}{2})^n\right], \tag{6}$$

where

$$\lambda_T = \left(\frac{2\pi\hbar^2}{mT}\right)^{1/2} \tag{7}$$

is the thermal wavelength of the nucleon, and $b_n's$ are the inversion coefficients given in refs. [20–22]. In eq. (6), V_q is the single particle potential energy and can be parameterized as

$$V_q(\rho,\delta) = a(\rho/\rho_{NM}) + b(\rho/\rho_{NM})^\sigma \ + V^q_{\rm asy}(\rho,\delta). \tag{8}$$

The parameters $a,\ b$ and σ are determined by the saturation properties and the compressibility K of symmetric nuclear matter, i.e.,

$$a = -29.81 - 46.90\frac{K+44.73}{K-166.32}\ (\text{MeV}), \tag{9}$$

$$b = 23.45\frac{K+255.78}{K-166.32}\ (\text{MeV}), \tag{10}$$

$$\sigma = \frac{K+44.73}{211.05}. \tag{11}$$

The isospin-independent term should also contain a momentum-dependent part which is important for some dynamical observables, such as the collective flow (e.g., [23–25]), but is not essential for other observables, such as the ratio of preequilibrium neutrons to protons [19]. Effects of momentum-dependent interactions on thermal properties were studied recently in refs. [26,27] and were found to have only small effects. We thus neglect the momentum-dependent interaction and concentrate on investigating effects of the isospin-asymmetric potential $V^q_{\rm asy}$. This potential is given by

$$V^q_{\rm asy}(\rho,\delta) = \partial w_a(\rho,\delta)/\partial\rho_q, \tag{12}$$

where $w_a(\rho,\delta)$ is the contribution of nuclear interactions to the symmetry energy density, i.e.,

$$w_a(\rho,\delta) = e_a\cdot\rho F(u)\delta^2, \tag{13}$$

and

$$e_a \equiv S_0 - (2^{2/3}-1)\frac{3}{5}E^0_F. \tag{14}$$

In the above, $u=\rho/\rho_0$ with ρ_0 the normal nuclear matter density; S_0 is the symmetry energy $S(\rho)$ at ρ_0 and is known to be in the range of 27-36 MeV [28]; and E^0_F is the Fermi energy at ρ_0.

For the function $F(u)$, we consider the following three forms: $F(u)=u^2$, u and $u^{1/2}$, which are taken form the results of typical microscopic many-body calculations. Then the corresponding symmetry potentials are, respectively,

$$V_{\rm asy}^{n(p)} = \pm 2e_a u^2\delta + e_a u^2\delta^2, \tag{15}$$

$$V_{\rm asy}^{n(p)} = \pm 2e_a u\delta, \tag{16}$$

and

$$V_{\rm asy}^{n(p)} = \pm 2e_a u^{1/2}\delta - \frac{1}{2}e_a u^{1/2}\delta^2, \tag{17}$$

where "+" and "−" are for neutrons and protons, respectively.

From the chemical potentials determined by eq. (6), we obtain the total pressure of the system from the Gibbs-Duhem relation,

$$\frac{\partial P}{\partial \rho} = \frac{\rho}{2}\left[(1+\delta)\frac{\partial \mu_n}{\partial \rho} + (1-\delta)\frac{\partial \mu_p}{\partial \rho}\right]. \tag{18}$$

The result can be separated into three parts, i.e.,

$$P = P_{\rm kin} + P_0 + P_{\rm asy}, \tag{19}$$

where $P_{\rm kin}$ is the kinetic contribution

$$P_{\rm kin} = T\rho\{1 + \frac{1}{2}\sum_{n=1}^{\infty} b_n(\frac{\lambda_T^3\rho}{4})^n\left[(1+\delta)^{n+1} + (1-\delta)^{1+n}\right]\}, \tag{20}$$

and P_0 is the contribution from the isospin-independent nuclear interaction

$$P_0 = \frac{1}{2}a\rho_0(\frac{\rho}{\rho_0})^2 + \frac{b\sigma}{1+\sigma}\rho_0(\frac{\rho}{\rho_0})^{\sigma+1}. \tag{21}$$

$P_{\rm asy}$ is the contribution from isospin-dependent part of the nuclear interaction, and it can be written as

$$P_{\rm asy} = 2e_a\rho_0(\frac{\rho}{\rho_0})^3\delta^2, \tag{22}$$

$$P_{\rm asy} = e_a\rho_0(\frac{\rho}{\rho_0})^2\delta^2, \tag{23}$$

and

$$P_{\rm asy} = \frac{1}{2}e_a\rho_0(\frac{\rho}{\rho_0})^{3/2}\delta^2 \tag{24}$$

for $F(u) = u^2,\ u$ and $u^{1/2}$, respectively.

The condition for mechanical stability follows from eq. (18) and can thus be determined straightforwardly. To evaluate the condition for chemical stability, we use the following relations:

$$\left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,P} = \left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,\rho} - \left(\frac{\partial \mu_n}{\partial P}\right)_{T,\delta} \cdot \left(\frac{\partial P}{\partial \delta}\right)_{T,\rho},$$
$$= \left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,\rho} - \left(\frac{\partial \mu_n}{\partial \rho}\right)_{T,\delta} \cdot \left(\frac{\partial P}{\partial \rho}\right)^{-1}_{T,\delta} \cdot \left(\frac{\partial P}{\partial \delta}\right)_{T,\rho}. \tag{25}$$

Knowing $\left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,P}$ and $\left(\frac{\partial P}{\partial \rho}\right)_{T,\delta}$ as functions of ρ, T and δ, we can then identify regions of the configuration space where chemical and/or mechanical instability occur. We first show in Fig. 1 and Fig. 2 these two quantities as functions of ρ at various T and δ. In the calculation $K = 200$ MeV and $F(u) = u$ are used. For comparison we also show in the left panel of Fig. 1 results for symmetric nuclear matter. In this case there is no chemical instability and the quantity $\left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,P}$ increases with both density and temperature. To understand this, we note that

$$\left(\frac{\partial P}{\partial \delta}\right)_{T,\rho} = \frac{2}{\delta} P_{\rm asy} + \frac{T\rho}{2} \sum_{n=1}^{\infty} (n+1) b_n (\frac{\lambda_T^3 \rho}{4})^n \left((1+\delta)^n - (1-\delta)^n\right), \tag{26}$$

$$\left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,\rho} = \left(\frac{\partial V^n_{\rm asy}}{\partial \delta}\right)_{T,\rho} + T\left[\frac{1}{1+\delta} + \sum_{n=1}^{\infty} (n+1) b_n \left(\frac{\lambda_T^3 \rho}{4}\right)^n (1+\delta)^{n+1}\right], \tag{27}$$

and

$$\lim_{\delta \to 0} \left(\frac{\partial P}{\partial \delta}\right)_{T,\rho} = 0. \tag{28}$$

Then, it can be shown that

$$\lim_{\delta \to 0} \left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,P} = \lim_{\delta \to 0} \left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,\rho}, \tag{29}$$

$$= 2 e_a F(u) + T\left[1 + \sum_{n=1}^{\infty} (n+1) b_n \left(\frac{\lambda_T^3 \rho}{4}\right)^n\right], \tag{30}$$

which is always positive as expected for symmetric nuclear matter. Furthermore, it increases with both density and temperature.

Mechanical instability is known to happen at intermediate densities corresponding to the mixed phase between the gas and liquid phases at subcritical temperatures. This is

clearly demonstrated by plotting $\left(\frac{\partial P}{\partial \rho}\right)_{T,\delta}$ as a function of ρ. It is interesting to examine this quantity at the low density limit. From the Gibbs-Duhem relation of eq. (18) and the expression for μ_q of eq. (6), we obtain

$$\lim_{\rho\to 0}\left(\frac{\partial P}{\partial \rho}\right)_{T,\delta} = \lim_{\rho\to 0}(T + a\frac{\rho}{\rho_0}) = T, \tag{31}$$

as in a dilute gas.

We note from eq. (25) that the quantity $\left(\frac{\partial \mu_n}{\partial \delta}\right)_{T,P}$ is singular along the boundary of mechanical instability where $\left(\frac{\partial P}{\partial \rho}\right)_{T,\delta} = 0$. This singularity is indicated by the spikes in Fig. 1 and Fig. 2. However, the height of these spikes between the boundaries of the gas phase and the mixed phase is relatively low. This is because at this boundary the last derivative in eq. (25) is also close to zero, i.e.,

$$\lim_{\rho\to 0}\left(\frac{\partial P}{\partial \delta}\right)_{T,\rho} = \frac{2}{\delta}\cdot \lim_{\rho\to 0} P_{\rm asy} = 0. \tag{32}$$

Although a nuclear system is always chemically stable in the low density limit as

$$\lim_{\rho\to 0}\left(\frac{\partial \mu_n}{\partial \delta}\right)_{P,T} = \frac{T}{1+\delta} > 0, \tag{33}$$

it starts to develop chemical instability at finite density once it becomes neutron-rich. In particular, it is seen that the boundary of mechanical instability shrinks while that of chemical instability expands as the isospin asymmetry δ increases. For example, at a temperature of T=8 MeV the mechanical instability gradually disappears but the chemical instability becomes more pronounced as δ increases from 0 to 0.6. Furthermore, in the mechanically unstable region the nuclear system can be chemically stable, but at higher densities chemical instability happens even in the mechanically stable region. This is more clearly shown in Fig. 3 where the pressure along the chemical (DS) and mechanical (ITS) spinodals are plotted as functions of density. Both the isothermal pressure and separation between the two spinodals increase with increasing δ. Therefore, not only the chemical but also the mechanical instability is strongly isospin-dependent.

The isospin dependence of mechanical and chemical instabilities at a fixed temperature is studied in more detail in Fig. 4 and Fig. 5. It is seen that the system is both mechanically

and chemically stable at low and high densities. At intermediate densities (e.g., $\rho/\rho_0 = 0.4, 0.5$) the system is mechanically unstable at low δ (e.g., $\delta \leq 0.2$ and $\delta \leq 0.4$ for $\rho/\rho_0 = 0.4$ and 0.5, respectively) and chemically unstable at intermediate δ (e.g., $0.2 \leq \delta \leq 0.4$ for $\rho/\rho_0 = 0.4$ and $0.4 \leq \delta \leq 0.6$ for $\rho/\rho_0 = 0.5$, respectively). The corresponding boundaries in the pressure-density plane are shown in Fig. 5. Again, the diffusive spinodal line is more extended than the isothermal spinodal. The isospin dependence of the pressure is also shown in this figure. We note that its strong dependence on δ is due to the significant $P_{\rm asy}$ contribution to the total pressure.

Both chemical and mechanical instabilities also depend on the isospin-dependent and -independent parts of the nuclear equation of state. To demonstrate this, we show in Fig. 6 and Fig. 7 the pressure as a function of density ρ (left panels) and isospin asymmetry δ (right panels) along the diffusive spinodals (upper windows) and isothermal spinodals (lower windows) at a constant temperature of $T = 10$ MeV by using the three forms of $F(u)$ and a compressibility of 380 and 200 MeV, respectively. From these two figures we observe the following interesting features. First, the diffusive spinodals are always more extended than the isothermal spinodals. Second, both DS and ITS depend on the form of $F(u)$, and this dependence is stronger for the stiff equation of state of $K = 380$ MeV. Third, from the right panels of these two figures one sees that it is both chemically and mechanically favorable for the system to be less asymmetric (smaller δ) in the liquid phase than in the gas phase. This result is consistent with that based on the energy consideration. Since the equation of state for asymmetric nuclear matter contains a $S(\rho)\delta^2$ term, it is therefore energetically favorable for it to separate into a liquid phase that is less asymmetric and a gas phase that is more asymmetric, rather than into two phases with equal isospin asymmetry. Finally, it is seen that there is a maximum isospin asymmetry for both DS and ITS. Along both DS and ITS the isospin asymmetry increases to a maximum value and then decreases as the density is reduced from the liquid phase towards the gas phase. As shown in both figures, the maximum isospin asymmetry is also sensitive to both the isospin-dependent and -independent parts of the nuclear equation of state.

III. SUMMARY AND DISCUSSIONS

Using various phenomenological equations of state, we have studied both the chemical and mechanical instabilities in hot isospin-asymmetric nuclear matter. Both instabilities are found to depend strongly on the isospin asymmetry of the nuclear matter. Also, in a chemically and mechanically stable asymmetric nuclear matter a lower neutron excess is favored in the liquid phase than in the gas phase. Furthermore, there is a maximum neutron excess in the mixed phase at intermediate densities. For all nuclear equations of state considered here, the boundary of chemical instability is found to be more extended than that of mechanical instability. However, the location of these boundaries in the (T, ρ, δ) space depends sensitively on both the bulk compressibility of nuclear matter and the density dependence of the symmetry energy. These results are relevant in understanding the significant differences observed in the fragment distributions from collisions involving isospin-symmetric and isospin-asymmetric nuclei at intermediate energies [4–6]. One scenario for nuclear multifragmentation is that the hot system formed in a reaction expands almost adiabatically into the mechanical instability region and then disassemble into clusters and nucleons due to the growth of density fluctuations (e.g. [29]). Great efforts have thus been devoted during the last decade (e.g., [30–34]) to incorporate the effects of density fluctuations into dynamical transport models. To describe nuclear multifragmentation from heavy ion collisions involving asymmetric nuclei, it will be of interest to extend these dynamical models to include also the isospin degree of freedom and its fluctuations.

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FIGURES

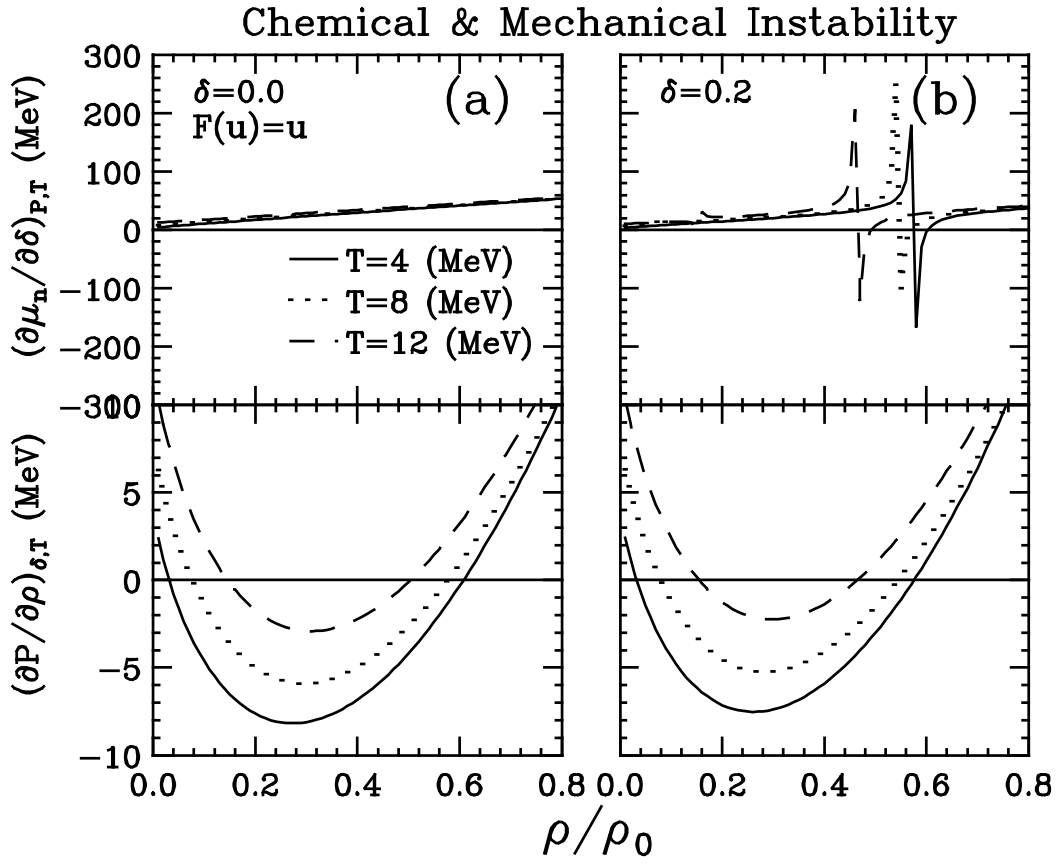

FIG. 1. Chemical (upper window) and mechanical (lower window) stability conditions as functions of density at fixed temperatures $T = 4$, 8 and 12 MeV for $\delta = 0.0$ (left panel), and $\delta = 0.2$ (right panel).

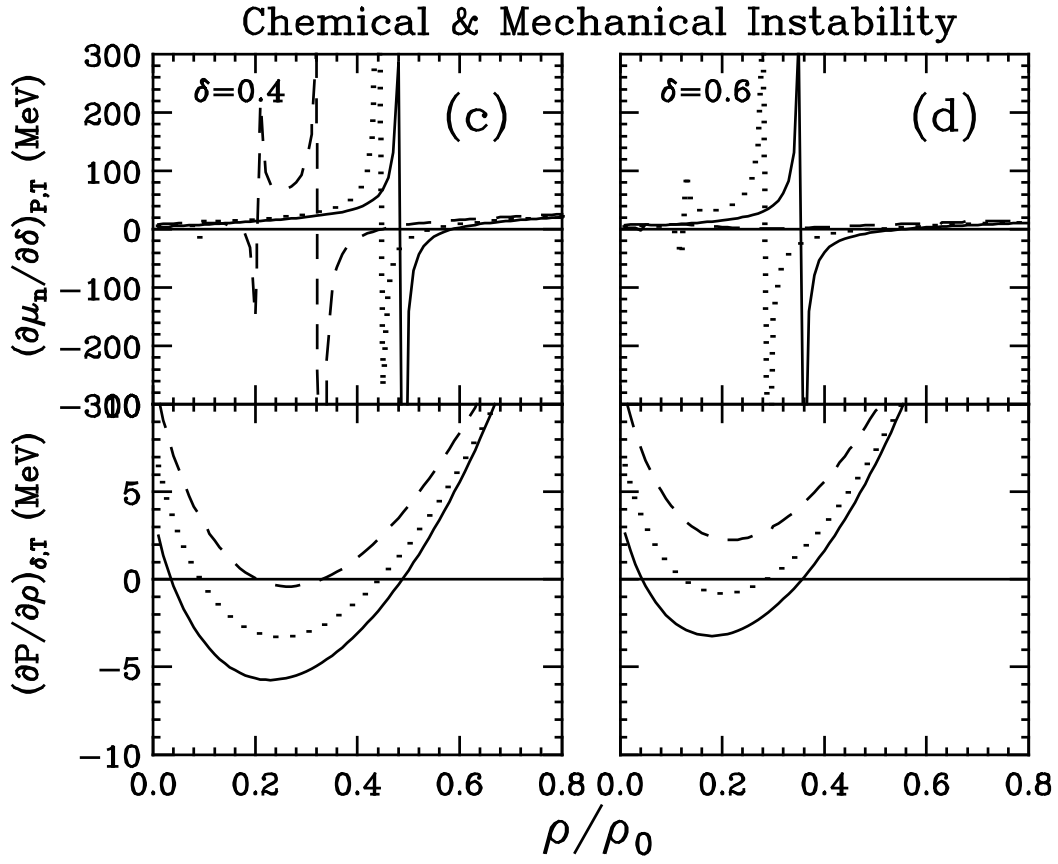

FIG. 2. Same as Fig. 1 but for $\delta = 0.4$ (left panel), and $\delta = 0.6$ (right panel).

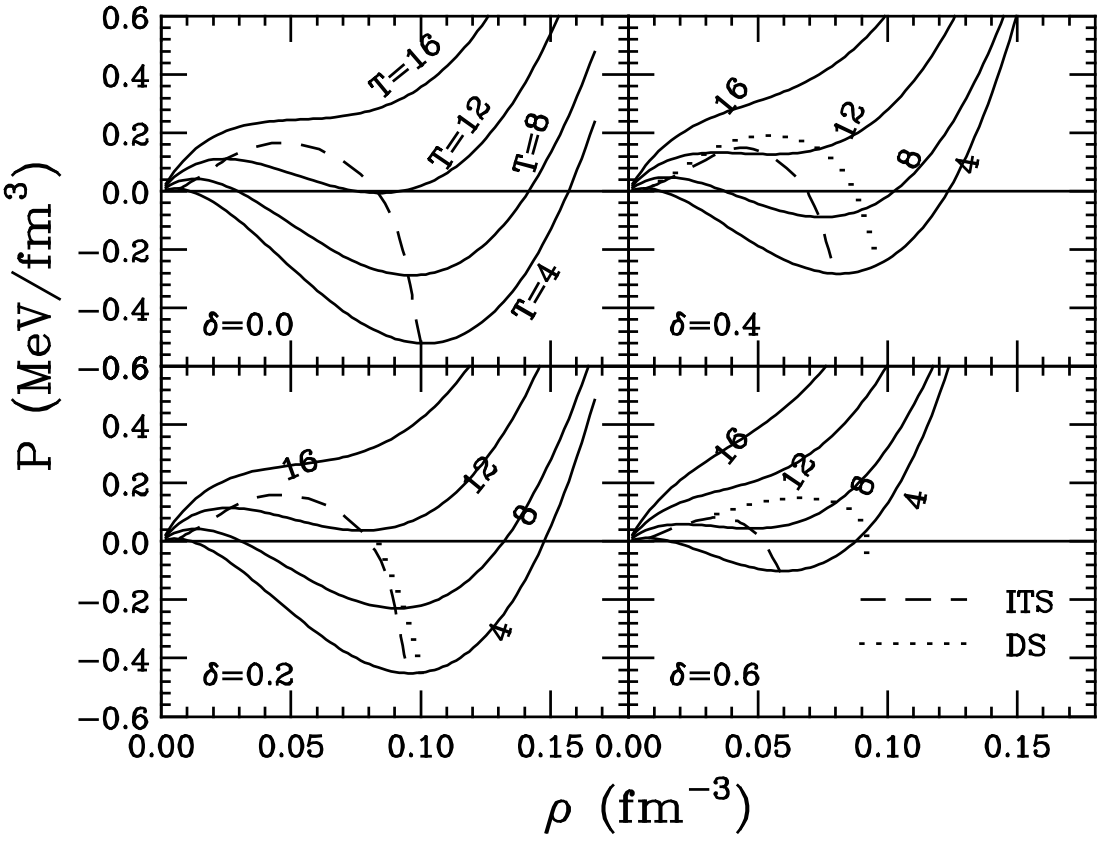

FIG. 3. Pressure as a function of density at fixed temperatures T = 4, 8, 12 and 16 MeV for δ = 0.0, 0.2, 0.4 and 0.6. The isothermal (diffusive) spinodals are plotted using dashed (dotted) lines.

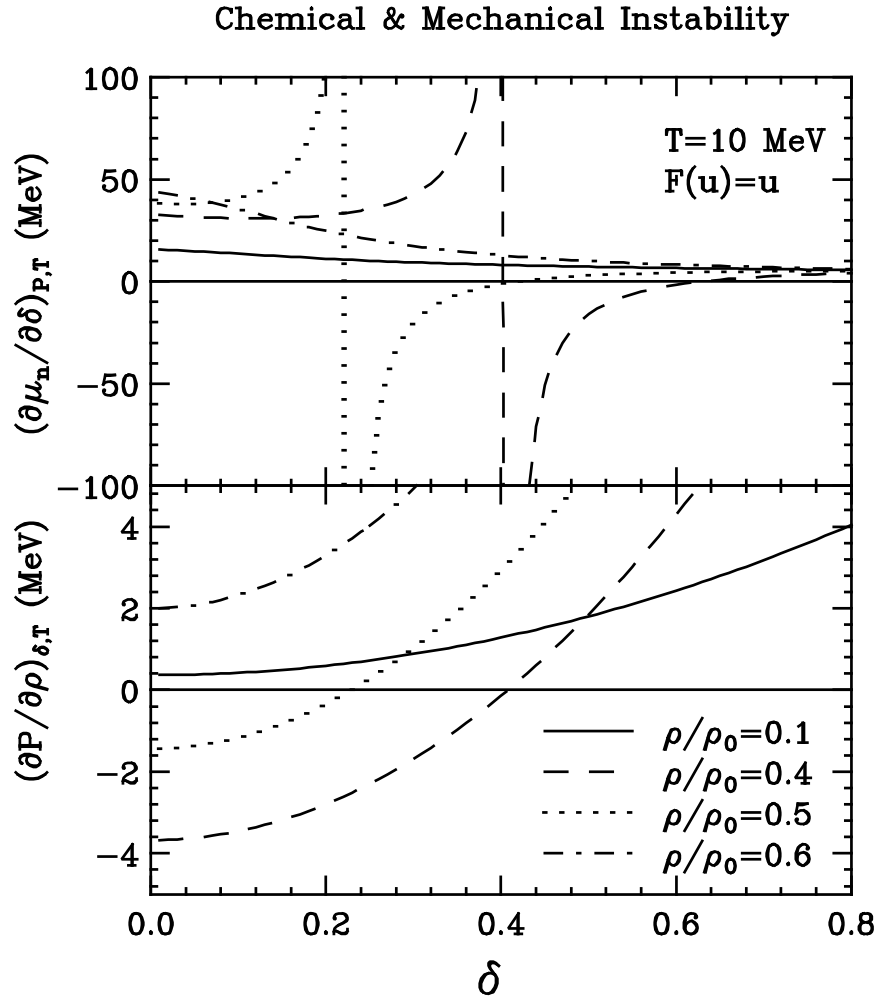

FIG. 4. Chemical (upper window) and mechanical (lower window) stability conditions as functions of δ at a fixed temperature $T = 10$ MeV and various densities.

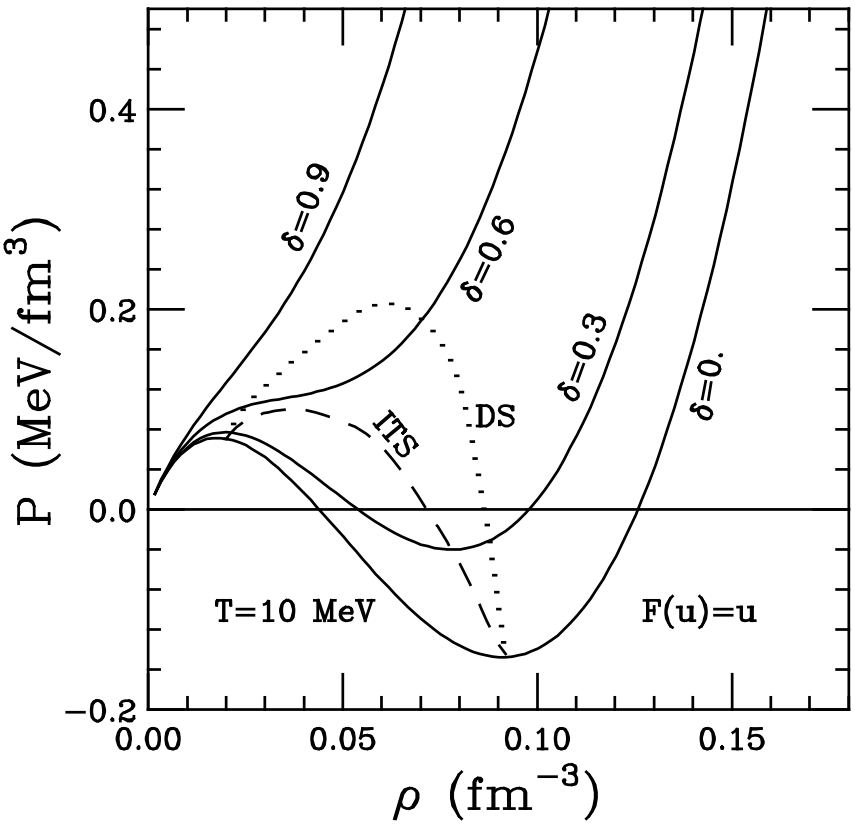

FIG. 5. Pressure as a function of density at a fixed temperature $T = 10$ MeV at various δ. The isothermal (diffusive) spinodals are plotted using dashed (dotted) lines.

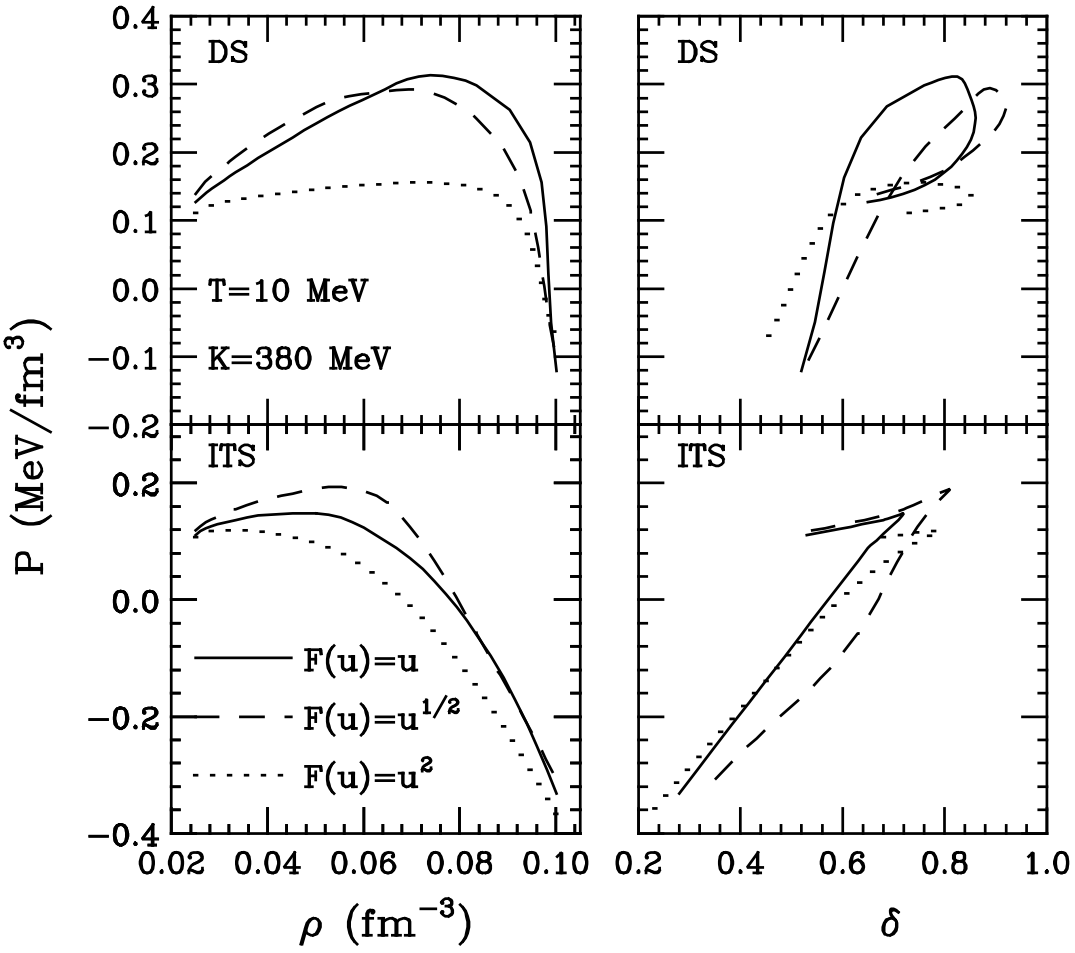

FIG. 6. Pressure as a function of density (left panel) and isospin asymmetry (right panel) at a fixed temperature $T = 10$ MeV along the boundary of diffusive spinodals (upper windows) and isothermal spinodals (lower windows) by using three forms of $F(u)$ and a compressibility of $K = 380$ MeV.

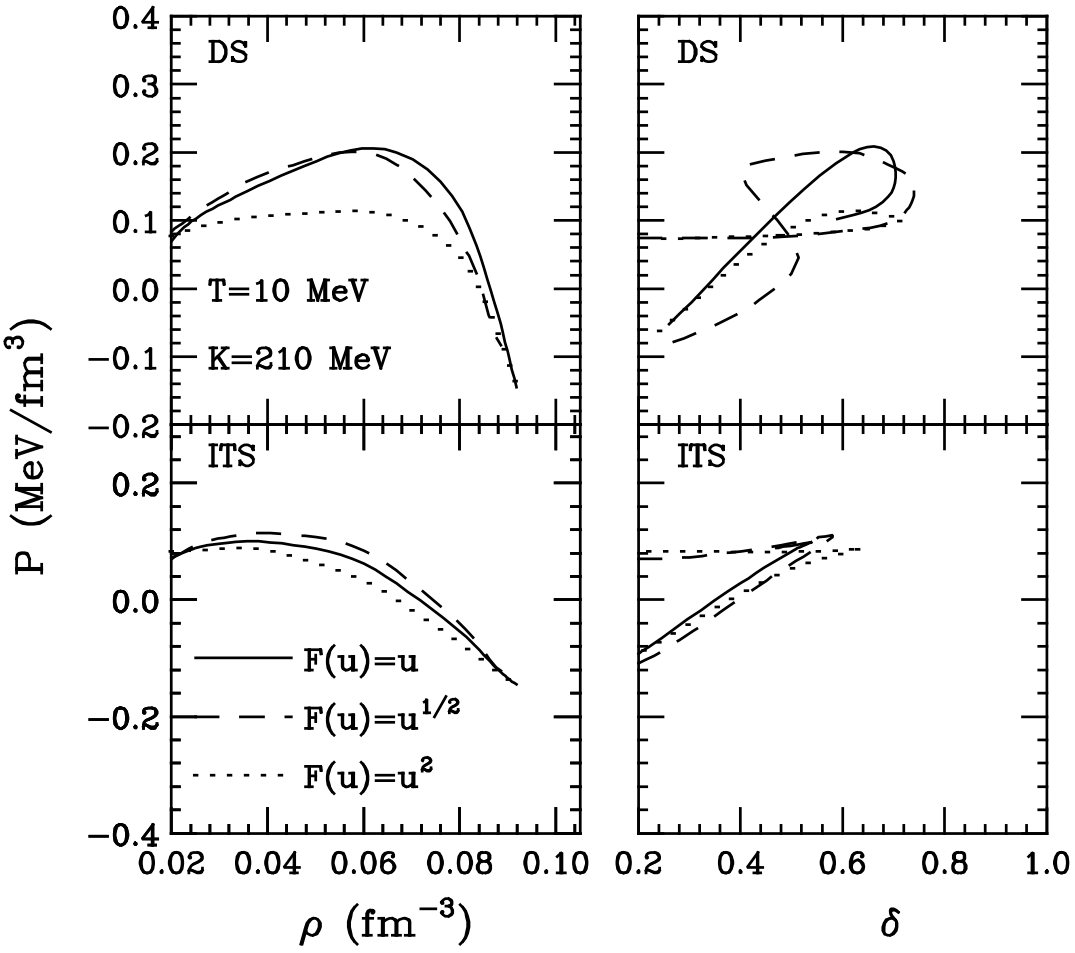

FIG. 7. Same as Fig. 6 for a compressibility of $K = 200$ MeV.